Fuel Containment of Auxiliary Fuel Tanks

March 1995

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15. Supplementary Notes

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16. Abstract

This report summarizes activity performed in support of the FAA's Fuel Containment research program. A review was made of previously performed pretest analysis and longitudinal test results for a double-wall cylindrical auxiliary fuel tank. A review was made of the Auxiliary Fuel System Installation Advisory Circular. Available data from recent, pertinent transport category airplane accidents and full-scale crash test results were discussed for their relevance to the Fuel Containment research effort. The fuel tank/airframe installation was defined for the next series of longitudinal- and vertical-impact tests. The outline of a proposed semiempirical procedure was developed. The procedure's potential would be for use in evaluating fuselage auxiliary fuel tank installations under dynamic loading utilizing available and pending test data.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAIB   British Air Accidents Investigation Board

CID   Controlled Impact Demonstration

ENV   Effective Normal Velocity

FAA   Federal Aviation Administration
FAATC   Federal Aviation Administration Technical Center
FAR   Federal Aviation Regulation
ft/s   feet per second

g   acceleration due to gravity
GSC   Galaxy Scientific Corporation

m/s   meters per second
ms   millisecond
M.S.   Margin of Safety

NASA   National Aeronautics and Space Administration

PATS   Pats, Inc.

R&D   Research and Development

s   Second

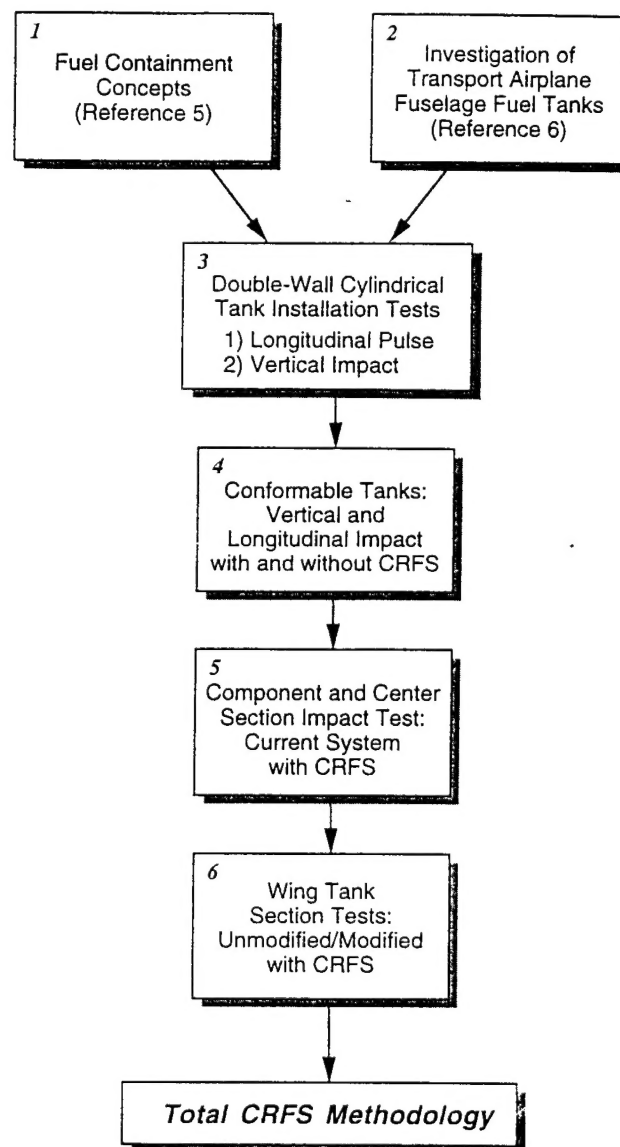TRC   Transportation Research Center

EXECUTIVE SUMMARY

The results of the Controlled Impact Demonstration (CID) crash test in 1985 indicated that alternatives to fuel additives for reducing or eliminating postcrash fire fatalities or injuries should be considered. The Federal Aviation Administration (FAA) initiated a program to investigate fuel containment concepts. This report summarizes work performed in support of the FAA's Fuel Containment research program.

This effort was concentrated into five areas. A review was made of pretest analysis and longitudinal test results for a double-wall cylindrical auxiliary fuel tank. A review was made of the Auxiliary Fuel System Installation Advisory Circular. Data from recent transport category airplane accidents and full-scale crash test results were discussed. The fuel tank/airframe installation was defined for the next longitudinal and vertical impact test. The outline of a semiempirical procedure to evaluate fuselage auxiliary fuel tank installations under dynamic loading was developed. The procedure was provided as a potential method to evaluate fuselage auxiliary fuel tank installations under dynamic loading using available and pending test data.

Several conclusions were made based on the analysis conducted in this program. A fuselage airframe and auxiliary fuel tank installation was suggested for the next phase of testing. Recent accident data have shown that the current auxiliary fuselage fuel tank test/analysis program is relevant to narrow-body airplanes with impact velocities in the range of severe, but survivable, accidents. Without supporting analytical or semiempirical procedures, testing alone is too limited, time consuming, and too costly an approach to evaluate auxiliary fuel tank performance under crash conditions.

1.   INTRODUCTION.

The three major domestic transport airplane manufacturers under contracts to the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) (references 1-3) performed a comprehensive evaluation of FAR 25 airplane accidents from 1960–1979. Postcrash fires were noted as a major area of concern. The results of the Controlled Impact Demonstration (CID) crash test in 1985 (reference 4) suggested that alternatives to fuel additives for reducing or eliminating postcrash fire fatalities or injuries should be considered. The FAA initiated a program to investigate fuel containment concepts. Figure 1 illustrates the overall program as it was initially proposed.
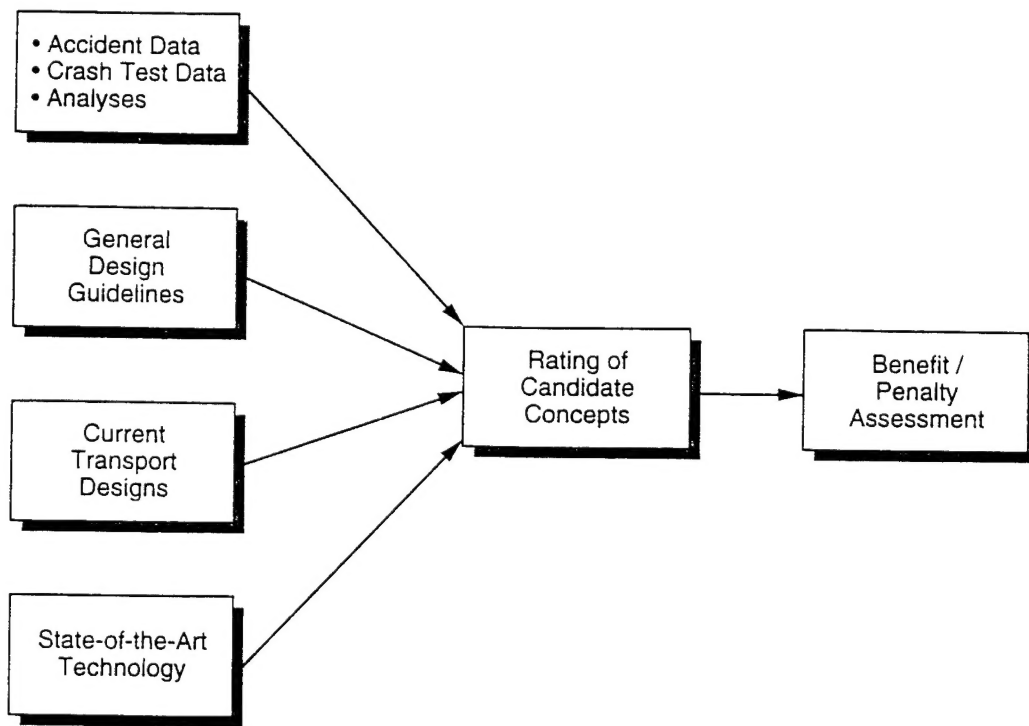

GSC-985-94.1

FIGURE 1. PROPOSED FUEL TANK INSTALLATION TEST PROGRAM

The tasks previously completed, before this current effort, are described in references 5-7. The flow diagrams for the initial "fuel containment concepts" and the subsequent "investigation of installations under crash loads," are shown in figures 2 and 3. The most recent task (reference 7) included a longitudinal-pulse test of a fuselage section with a double-walled floor-mounted cylindrical auxiliary fuel tank. The FAA sponsored research also includes a vertical impact test of the same fuselage section with the same double-walled auxiliary fuel tank installed (reference 8). This latter test also included overhead bins and seats as well as the double-wall cylindrical auxiliary fuel tank, which is being evaluated by the FAA, research with regard to auxiliary fuselage fuel tank installations performance under crash impact conditions is ongoing. The objectives of the current effort described herein, is as follows:

a.   Establish the auxiliary fuel tank installation/airframe configuration combination to be tested in the next phase of the program.

b.   Provide a preliminary proposed procedure by which auxiliary fuselage fuel tank installation performance under crash impact conditions can be evaluated simply.
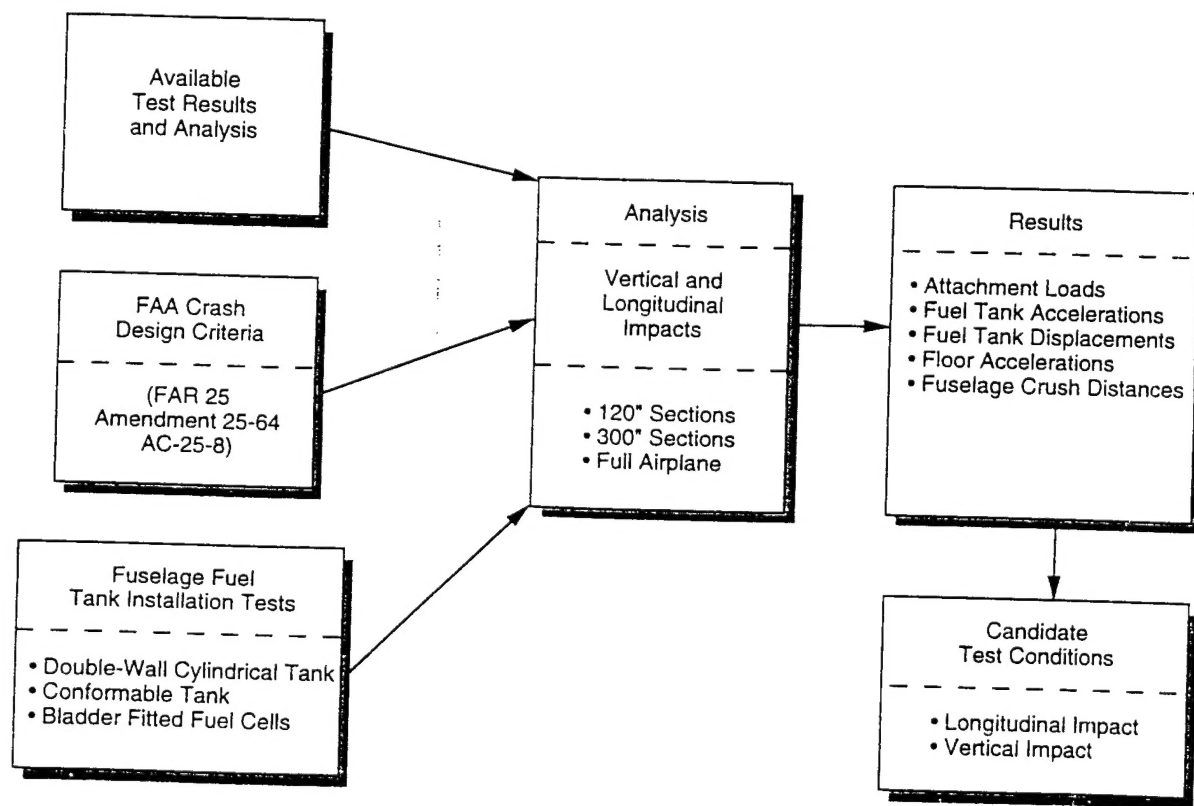

FIGURE 2. TRANSPORT CATEGORY AIRPLANE FUEL CONTAINMENT CONCEPTS

The next phase in the FAA Fuel Containment program includes the analysis and testing of other types of auxiliary fuel tank installations. This document describes the activities associated with

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establishing the test criteria, evaluating auxiliary fuel tank installation guidelines, analyzing the fuel tank behavior, and procuring of the tank system. The primary elements of this program are:

a.   A review of the double-wall auxiliary fuel tank longitudinal test (as it pertains to conformable tanks).

b.   A review of the Auxiliary Fuel System Installation Advisory Circular.

c.   Review of available recent pertinent transport category accidents and full-scale crash test results.

d.   An assessment of and determination of a fuel tank/airframe installation for the next longitudinal and vertical impact test.

e.   The outline of a procedure to be used to evaluate fuselage auxiliary fuel tank installation performance under dynamic loading using available and pending test data.

GSC-985-94.3

FIGURE 3. INVESTIGATION OF TRANSPORT AIRPLANE FUSELAGE FUEL TANK
INSTALLATIONS UNDER CRASH CONDITIONS

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2.   PERFORMANCE.

2.1   REVIEW OF PRETEST ANALYSIS AND TEST DATA FOR DOUBLE-WALL TANK.

Reference 6 describes the pretest analysis performed in support of the testing of three auxiliary fuel tank installations in a crash environment. The analyses used KRASH models to evaluate responses to both longitudinal and vertical crash impact forces. The auxiliary fuel tank installations analyzed are:

  a.   Double-wall cylindrical strap-in auxiliary tank.
  b.   Conformable tank with a bladder and supported within a dedicated structure.
  c.   Bladder cells fitted in a lower fuselage.

For the longitudinal direction forces, nine cases were studied which encompassed airplane frontal impacts, combined airplane vertical and longitudinal impacts, and an airframe longitudinal pulse excitation. The latter condition (reference 6) represents the type of test that was performed on the double-wall cylindrical strap-in auxiliary tank. This type of test is also planned for the conformable tank. The analysis shows that for the double-wall configuration the fuel tank response (peak acceleration) will be amplified (<10 percent) when compared to the floor response. The analysis for this condition considered a longitudinal pulse of:

Peak acceleration	=	14.2 g's
Velocity change	=	36.2 ft/s
Pulse rise time	=	0.07 s

For the vertical direction impact condition a 25 ft/s velocity change condition was analyzed. Several KRASH models were used, including: a 6-bay, 20-inch frame spacing airframe section; a 5-bay, 60-inch frame spacing airframe section; and the CID stick model. The 6-bay airframe section is considered most representative of the potential test configuration. The results from these analyses show that peak responses of 6.8 g's to 10.2 g's on the floor and 6.5 g's to 16.1 g's at the fuel tank are possible, depending on fuel tank weight and stiffness characteristics. These initial data show that an impact velocity between 25 and 35 ft/s is realistic.

The double-wall cylindrical tank analysis results were interpreted for the conformable tanks for the following attachment conditions:

  a.   Passenger floor supported tanks: double-wall tank results are applicable, although acceleration responses could be altered by the fuel tank mass and attachment stiffness.

  b.   Cargo floor mounted tanks: no analysis was conducted for this attachment configuration.

  c.   Combined passenger floor and fuselage attachment: this is the most prevalent configuration. The tank is located in the lower fuselage cargo compartment. The designs reviewed employ integral attachments to transfer all loads to predetermined load paths. The struts are

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attached at pin joints on both the tank and the body structure. Spherical bearings are installed at both joints to provide for relative motion between the tank and structure due to fuselage deflections from pressures and tank loads. Tank loads are transferred into the frames and skin by added support structure between body frames. The fuel and vent lines that connect the auxiliary tanks to the main fuel system incorporate drainable and vented shrouds. Additionally, these lines are designed to break away from the auxiliary tank. Sufficient stretch is provided to accommodate tank movement without causing fuel spillage. Hoses that are required to stretch are subjected to what is called a guillotine test. The hose is pressurized and clamped at both ends to simulate its mounting in the aircraft, then a sharp-pointed load is applied in the middle of the hose. The hose must not leak when stretched to its maximum.

This configuration is being considered for future projects. The effort to obtain the fuel tanks and the associated hardware, as well as provide for a proper installation, requires the following:

        a.   Fuel tank and installation layout.
        b.   Adaptability of the tank installation to FAA furnished airframe section.
        c.   Tank-passenger floor links and associated stress/load data.
        d.   Passenger floor reinforcement requirements.
        e.   Tank-airframe drag links and associated stress/load data.
        f.   Airframe reinforcement requirements.
        g.   Tank and attachment fittings crash design load factors.
        h.   Fuel and vent line routing.
        i.   Hose stretch and tear strength.

Reference 7 describes the longitudinal pulse test of a fuselage section in which seats and floor-mounted auxiliary fuel tanks are installed. The following is a review of the data that may influence future conformable tank tests:

        a.   A 7500-pound static pull test produced a 0.375 inch longitudinal deflection of the fuel tank. Thus, the fore-aft direction stiffness is 20,000 lb/in. Based on a fuel tank weight, including 2,000 lbs of water, of 2,300 lbs, the natural frequency of the installation is 9.2 Hz and the natural period is 0.109 second in the fore-aft direction.

        b.   During the high-energy dynamic pulse test, the sled acceleration was 13.0 g's. The average of four floor accelerometers was 13.7 g's (12.9, 13.1, 13.1 and 15.0 g's) and the two fuel tank accelerometers recorded 13.7 g's and 14.0 g's. Thus, the dynamic amplification factor can be considered between 1.054 and 1.076. The two lower energy pulse tests produced amplification factors of 1.08 or less. The responses at the high energy test conditions are shown in figure 4.

        c.   The high-energy test provides a sled pulse which is close to symmetrical. The rise time to the peak g occurs at 0.084 second. The velocity change of 38.6 ft/s indicates a total pulse duration of 0.185 second.

        d.   The dynamic amplification of a single degree of freedom depends on the system natural frequency and damping, the pulse rise time, and the pulse shape. For a symmetrical

triangular pulse exhibiting a 0.084 second rise time and highly damped system (0.25 critically damped) with a natural frequency of 9.2 Hz, an amplification factor of 1.08 is reasonable.

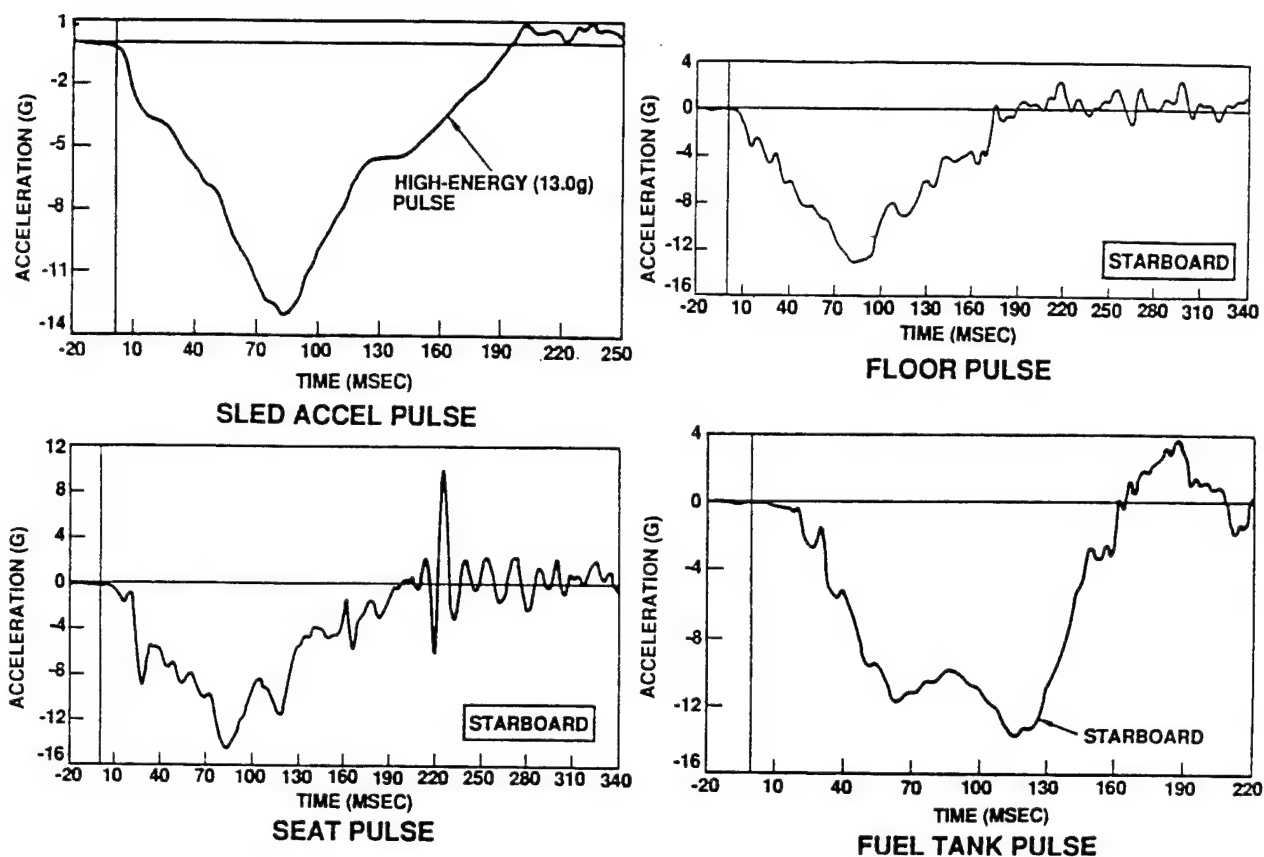   e.   No auxiliary fuel tank or attachment failures were experienced during the testing.

FIGURE 4. AUXILIARY FUEL TANK TEST LONGITUDINAL DIRECTION PULSES

The capability of the double-wall auxiliary fuel tank was estimated in reference 7 to be as high as 14.6g sled pulse and a 43.2 ft/s velocity change. These empirical estimates are based on available information, namely (1) dynamic test measurements obtained during the longitudinal pulse tests, and (2) analysis data provided in certification of such installations.

The tests showed that an auxiliary tank filled with 2,000 lbs of water excited to 13.5 g's of longitudinal acceleration, produces cradle strains equal to a similar tank filled with 2,350 lbs of water when exposed to 9 g's of static forward load. When the weight and g's are factored in (2000 x 13.5/2350 x 9.0), the dynamic to static equivalence on this test is approximately 1.28:1.0. The actual measured sled acceleration pulse 13.0 g's and velocity change 38.6 ft/s, based on an available Margin of Safety (MS) of between 2 and 12 percent. The capacity of the installation therefore was estimated to be between 13.3 g's and 14.6 g's and between 39.4 and 43.2 ft/s velocity change noted previously and in reference 7.

The above discussion of the documented double-wall auxiliary fuel tank installation analysis, and test results suggest the following:

a.   Pretest analysis can provide useful information to not only help establish test conditions, but also to evaluate and understand the results.

b.   Critical data that are needed consist of:

(1)   auxiliary fuel tank system natural frequency: static pull test,
(2)   9 g's static load analysis: certification report, and
(3)   critical locations and associated M.S.
(4)   Static Ultimate Load tests results where conducted.

c.   The system appears linear up to failure, which implies that dynamic-static equivalences might be used.

d.   A procedure to qualify fuselage mounted auxiliary fuel tank installations for dynamic loading conditions may be possible with the integration of test data and analytical techniques.

2.2   REVIEW OF AC 25-8, "AUXILIARY FUEL SYSTEM INSTALLATION".

AC 25-8, "Auxiliary Fuel System Installation" (reference 9) was reviewed relative to conformable tank testing. The comments on Chapter 1 "Fuel System Installation Integrity and Crashworthiness" are:

a.   Paragraph 1a. acknowledges that survivable accidents have occurred at vertical descent velocities greater than the 5 ft/s. Within that paragraph it states that either the tank material should have resilience and flexibility, or the installation shall provide extra clearance from structure that can be crushed or protected from primary structure that is not expected to crush.

It seems that there is recognition that the survivable sink rate is greater than 5 ft/s, however, what that level is has not been addressed. FAA fuselage section and full-scale tests, along with seat dynamic test requirements, suggest that a survivable vertical descent rate of between 25 ft/s and 35 ft/s may be realistic. Furthermore, the crush distance forward and aft of the wing trailing edge bulkheads can experience crush distances of more than 10 inches.

b.   Paragraph 1b(6) suggests that a crashworthiness analysis, or the equivalent, show that the airplane lower fuselage and the auxiliary fuel tank supporting structure are able to withstand the crash loads described in paragraph 25.561. The dynamic loads defined by the crashworthiness analysis should be accounted for in the stress analysis.

The reference to crash loads in paragraph 25.561 is in the form of ultimate inertia forces (static load factors) acting separately in different directions:

(1)	upward	3.0 g's
(2)	forward	9.0 g's
(3)	sideward	3.0 g's
(4)	downward	6.0 g's
(5)	rearward	1.5 g's

The dynamic loads are accounted for in the analysis by considering fitting factors, i.e., 1.15 on top of the static load factors. They are not accounted for by using floor dynamic test pulses or by performing an analysis of the structure behavior in a severe, but survivable crash impact scenario.

      c.   Paragraph 1b(7) suggests that a satisfactory vehicle structural crush distance to avoid auxiliary fuel tank ground contact be based on the loading condition of paragraph 25.561 (b) and be specified where necessary by tests. The analysis should identify failure modes and define the interaction between the tank adjacent structures and adjacent tanks.

The problem is that the survivable crash environment is much more severe than the loading conditions. The vertical drop tests of narrow-body airplane sections performed by the FAA Technical Center (FAATC) and NASA Langley demonstrate the degree of structural crush distances that are experienced. The FAA section drop test with the double-wall cylindrical auxiliary fuel tank installation will indicate the interface between the fuel tank and ground.

      d.   Paragraph 1b(8) states that structural deformation must be shown to be controllable and predictable, as required by paragraph 25.965.

Paragraph 25.965 refers to fuel tank vibration tests. This paragraph is concerned with the design of the tank to withstand internal pressures developed because of airplane performance. This requirement does not consider the development of internal pressures during the crash impact.

      e.   Paragraph 1b(11) states that the bottom and lower tank structure are adequately protected against rupture in crash landings.

The degree to which this protection is to be afforded depends on the crash impact conditions being considered.

The above discussion describes some guidelines provided to ensure that the installation of fuselage auxiliary fuel tanks will not jeopardize occupant safety in a crash environment. The major concern, considering the ongoing FAA Fuel Containment Research and Development program, is that the guidelines are premised on static load factors. These may not be consistent with the transport airplane crash survivable envelope.

2.3   REVIEW OF RECENT ACCIDENTS AND RELATED FULL-SCALE CRASH TESTS.

The review of the Auxiliary Fuel System Installations AC 25-8 clearly indicates that there is a discrepancy between the static load factors that the guidelines address and the dynamic loads associated with the impact conditions that exist for severe, but survivable crashes. Figure 5

(reference 1) shows that there is a wide range of accident conditions that confront a transport category airplane. Some accidents, such as the air-ground collisions, both controlled and uncontrolled, are most likely outside the realm of practical design considerations. Others, such as wheels-up and retracted gear landings are minor crashes because of the lack of serious injuries or fatalities that are experienced. It is these types of accidents that the AC 25-8 appears to address. However, there are several accident types that are more representative of the impact conditions where fuselage auxiliary fuel tank installations should maintain sufficient structural integrity for passenger safety. These types of accidents; i.e., undershoot landing, hard landing, gear collapse, overshoot, and impact with obstacles, can be identified by two broad crash scenarios, ground-to-ground and air-to-ground. Characteristics of impact parameters for a ground-to-ground scenario are

     a.   embankment or slope impact, nonrigid terrain;

     b.   forward velocity, 40 to 150 knots (64.4 to 241.5 ft/s) - average = 83 knots (133 ft/s), (below 57 knots [92 ft/s] the fuselage would normally remain intact); and

     c.   sink speed < 5 ft/s.

CC   – CONTROLLED COLLISION W/GROUND
UC   – UNCONTROLLED COLLISION W/GROUND
US   – UNDERSHOOT
HL   – HARD LANDING
WU   – WHEELS UP
RG   – RETRACTED GEAR
GC   – GEAR COLLAPSE
OS   – OVERSHOOT
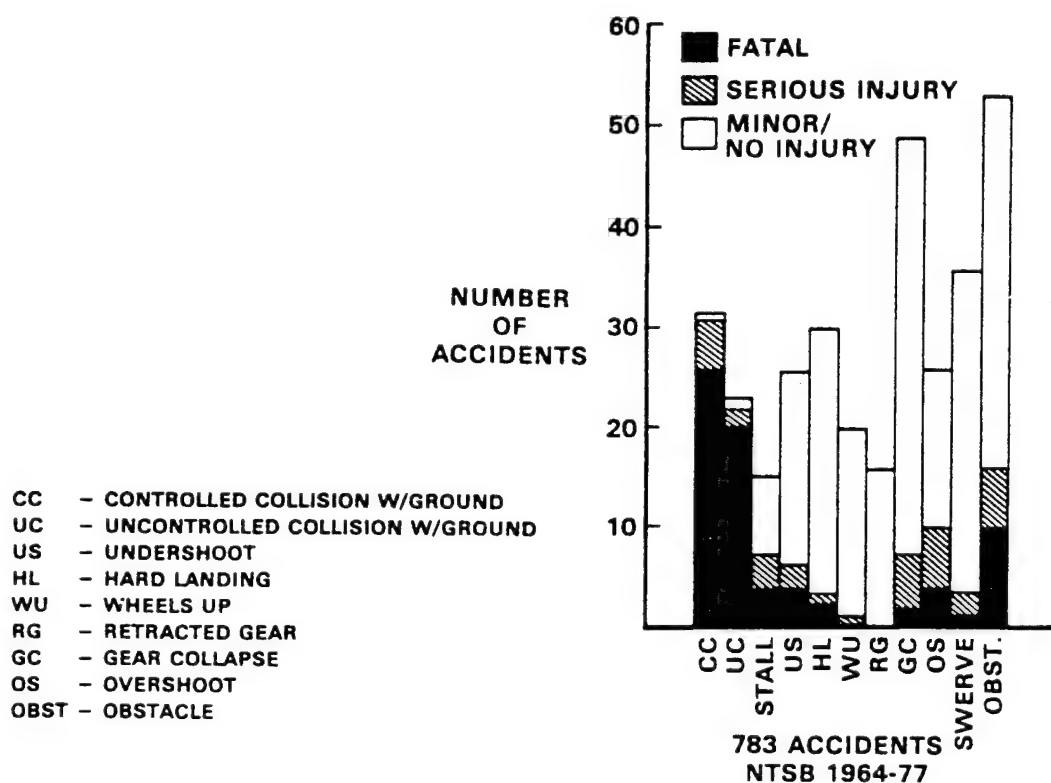OBST – OBSTACLE

783 ACCIDENTS
NTSB 1964-77

FIGURE 5. INJURY SEVERITY AS A FUNCTION OF ACCIDENT TYPE

The characteristics of an air-to-ground scenario are

     a.   forward velocity, from stall to takeoff velocity, 150 knots (242 ft/s);

b.   sink speed, (vertical velocity) 10 to 40 ft/s range, 20 ft/s average;

c.   pitch attitude, - 7 to + 15 degree range, -4 to + 4.7 degree average;

d.   roll attitude, 0 to 42 degree range, 17 degrees average;

e.   yaw attitude, 0 to 10 degree range, 5 degrees average; and

f.   sloped ground, nonrigid terrain.

Because of these and other studies the FAA decided that representative FAR 25 seat dynamic test pulses were:

a.   Combined vertical (0.866)-longitudinal (0.5) - resultant velocity change = 35 ft/s, resultant peak acceleration = 14 g's, rise time = 0.08 second.

b.   Longitudinal (10 degrees yaw) - resultant velocity change = 44 ft/s, resultant peak acceleration = 16 g's, rise time = 0.09 second.

There are several FAR 25 category airplane full-scale crash tests and accidents that provide data and are pertinent to crash design requirements for auxiliary fuel tank installation. These selected accidents/tests should be evaluated considering the accident study data, subsequent analyses, and current seat dynamic test requirements.

Two recent accidents that have been investigated by the British Air Accidents Investigation Branch (AAIB) provide some insight into the types of damage and occupant loading that is experienced during severe, but survivable crashes. The first was the B 737-400, G-OBME, which occurred near Kegworth, Leicestershire, England, on January 8, 1989. This accident is discussed in the AAIB aircraft accident report of April 1990 (reference 10). The report states that upon leaving Heathrow airport enroute to Belfast, the crew experienced engine difficulties and believing that the number 2 engine had suffered damage, shut it down. The crew initiated a diversion to the East Midlands Airport and initiated an instrument approach landing. The aircraft initially struck a field next to the eastern embankment of the M1 highway and suffered a second severe impact on the sloping western embankment of this highway.

This accident resulted in the initial deaths of 39 passengers, with 8 more deaths later from their injuries. Of the other 79 occupants, 74 had serious injuries. The airplane suffered severe impact damage and the fuselage broke into three sections. The nose section traveled the greatest distance, toward the western embankment of the M1, while the center section remained upright with the wings attached. The tail section buckled over the right section of fuselage, just aft of the wing. The engines were found at their wing stations even though they had suffered ground impact damage. There was extensive damage to the floor and seats, which varied by location. The landing gear failed rearward on initial impact.

The initial impact parameters were noted as:

Pitch	=	12.0 to 14.0 degrees nose up
Roll	=	3.0 to 5.0 degrees right wing low
Yaw	=	3.5 to 5.5 degrees nose left
Airspeed	=	113.0 knots (182 ft/s)
Rate of descent	=	8.5 to 16.0 ft/s
Flight path angle	=	2.5 to 5.0 degrees

The second impact parameters were noted as:

Pitch	=	9.0 to 13.0 degrees nose down
Roll	=	1.5 to 3.5 degrees right wing low
Yaw	=	-1.0 to 1.0 degree
Horizontal velocity	=	73.7 to 95.1 knots
		118.6 to 153.1 ft/s
Vertical velocity	=	21.6 to 28.0 knots
		34.8 to 45.1 ft/s
Resultant velocity	=	76.6 to 97.2 knots
		123.3 to 156.5 ft/s
Flight path	=	16.4 degrees

A KRASH computer model analysis produced mid-fuselage (center section) decelerations of:

a.	longitudinal	=	26.1 g's peak (17.8 g's fundamental)
		=	0.035 second rise time (0.07 second duration), and
b.	vertical	=	23.0 g's peak
		=	0.050 second rise time (0.10 second duration).

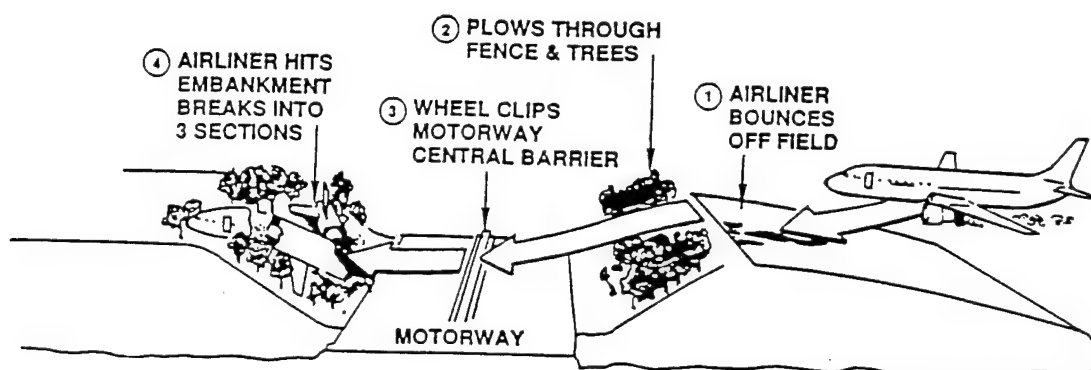The Kegworth accident is depicted in figure 6.

In a more recent accident, an SAS MD-81 crashed near the Stockholm airport in December 1991. This accident has also been analyzed using KRASH. The preliminary assessments of the impact parameters (reference 11) are as follows:

      a.   The airplane reached an altitude of 2000 feet on takeoff, but experienced double-engine failure due to ice shedding off the wings. This resulted in a crash landing with no power.

      b.   The aircraft flew through some tall trees in a right-wing low attitude. As it went through the trees outboard sections of the right wing came off.

      c.   Impact with the ground occurred with the airplane pitched nose-up, and yawed to the right. Contact with the ground occurred between the tailcone/right-engine nacelle, right main landing gear, and the remains of the right wing.

d.   Impact parameters were estimated as:

Pitch attitude	=	4.5 degrees nose up
Roll attitude	=	24.0 degrees right wing down
Yaw attitude	=	13.0 degrees nose right
Flight path velocity	=	163.5 ft/s
Flight path	=	11.0 degrees
Descent rate	=	31.7 ft/s
Terrain	=	5.0 degrees downward slope

GRAPHIC DESCRIPTION OF ACCIDENT

KRASH ANALYSIS OF TRANSPORT AIRPLANE ACCIDENT
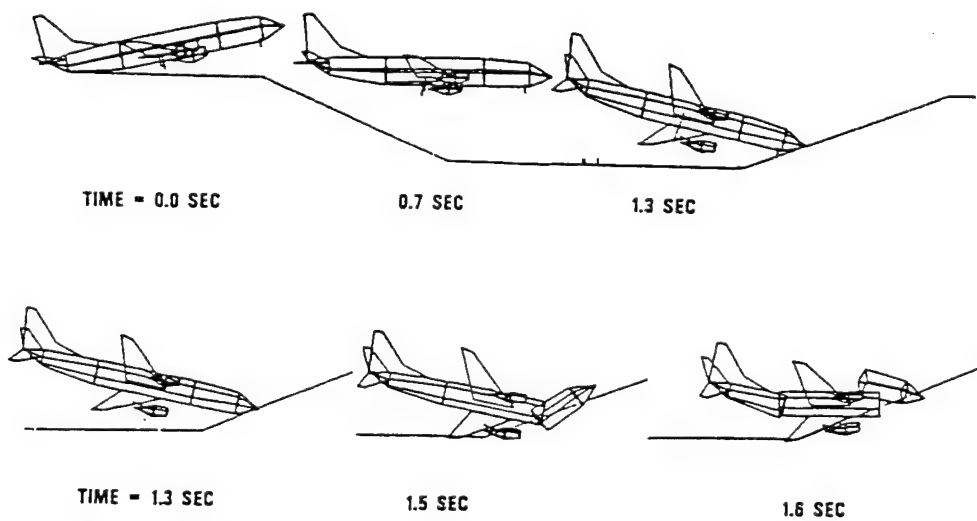

FIGURE 6. KEGWORTH ACCIDENT SCENARIO

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e.   Damage consisted of

    1.   two major fuselage breaks; (1) between body stations 560 and 579 and (2) between body stations 984 and 1117;
    2.   separation of both main landing gear;
    3.   extensive damage to the right wing: separated at stub;
    4.   impact damage to left wing: fuel tanks intact; and
    5.   several seats damaged: various types.

f.   There were no fatalities, some serious injuries, and mostly minor injuries.

g.   The investigation results showed substantial forward fuselage crush.

Several other accidents and/or crash tests have been analyzed using KRASH, including a wide-body transport airplane accident that occurred in the Florida Everglades (reference 12). The impact conditions were:

Roll attitude	=	28.0 degrees left wing down
Pitch attitude	=	0.8 degree nose up
Yaw attitude	=	0.0 degree
Roll rate	=	0.0 degree
Pitch rate	=	0.4 degree nose up
Yaw rate	=	2.6 degrees nose left
Longitudinal velocity	=	353.0 ft/s
Vertical velocity	=	37.0 ft/s
Pull up maneuver	=	1.6 g's lift
Terrain	=	6.0 to 12.0 in. of water on top of a 67-in. soft-mud base

Typical of a severe transport airplane crash, the airplane experienced two major breaks; however, of the 177 occupants on board, 77 survived. Figure 7 depicts the trail of damage and airframe breakup.

Another KRASH analysis was performed using data from an FAA conducted full-scale ground-to-ground crash test of a L-1649 airplane that was performed in 1964 (reference 13). The test sequence involved:

a.   a 160,000 pound: maximum takeoff gross weight airplane accelerated up to 112 knots (180 ft/s) climb-out speed,

b.   the removal of the main and nose gear by barrier impact,

c.   severance of the right wing by pole barriers,

d.   contact of right wing with a 30-degree sloped earthen mound,

e.   forward fuselage contact with a 6-degree slope,

f.   airplane override of the 6-degree slope, and

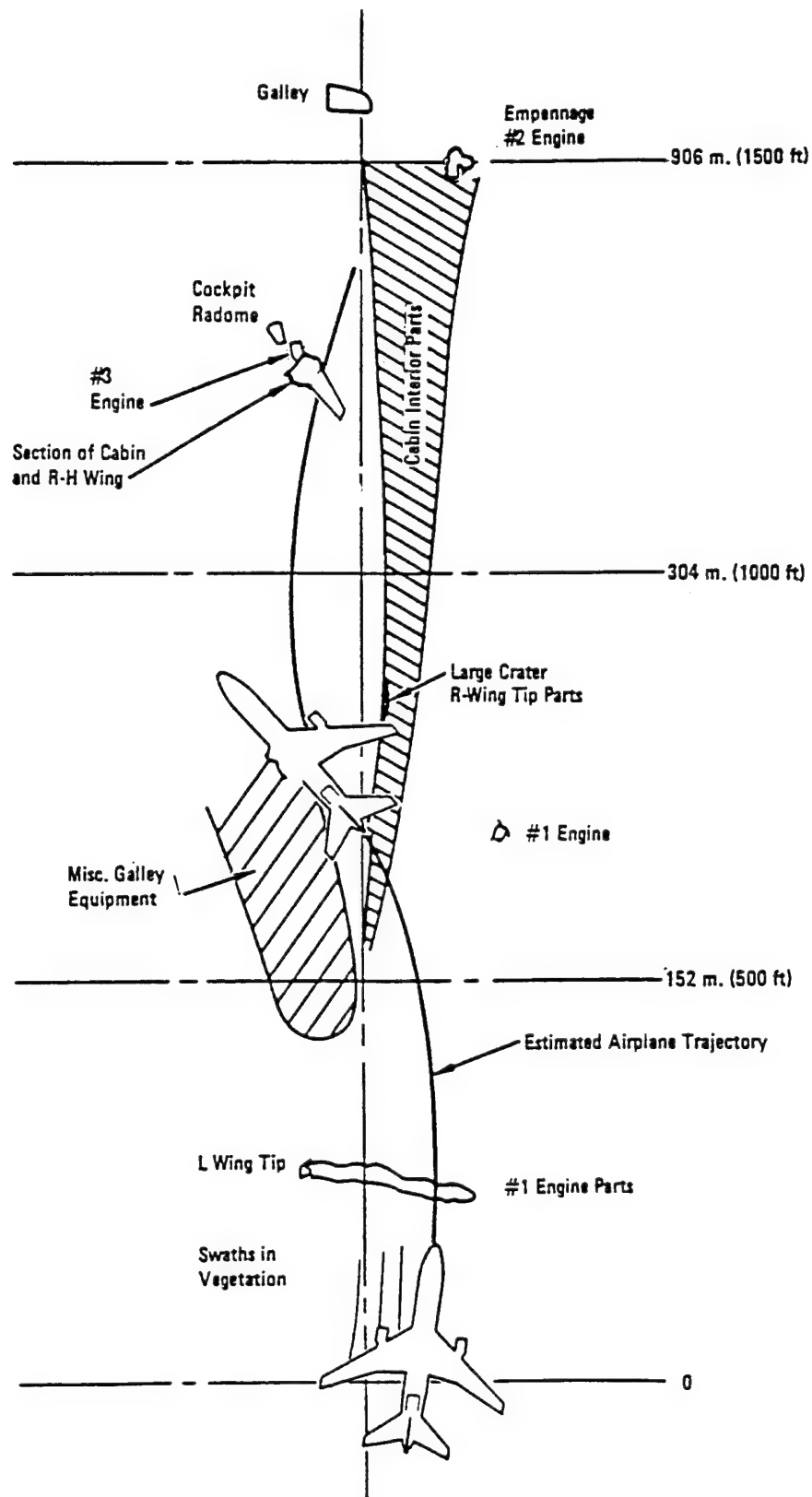g.   subsequent contact with a secondary 20-degree slope.

FIGURE 7. L-1011 ACCIDENT DAMAGE AND BREAKUP

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The test sequence was designed to incorporate several potential crash scenarios including:

a.   a hard landing, with a high rate of sink, causing failure of landing gear and damage to its supporting and surrounding structure (representative of a Montego Bay January 1960 accident);

b.   a low wing impact with the ground, such as the accident at JFK airport in New York in November 1962; and

c.   an impact into large trees in an off-airport forced landing. An example of this is the accident that occurred near Richmond, VA, in November 1961.

The initial slope impact occurred with an airplane forward velocity of 172 ft/s. This produced an effective sink speed normal velocity (ENV) of 18.5 ft/s. This was not sufficiently severe to produce a fuselage break. The impact onto the second slope (20-degree) at a forward velocity of 103 ft/s produced an ENV of 37.5 ft/s. This latter impact was severe enough that the airplane experienced two fuselage breaks, one aft of the nose section and the other near the wing trailing edge, as shown in figure 8. Besides the loss of all the gears upon barrier impact, there was extensive wing damage and loss of simulated fuel in the wing tanks due to pole and mound impact. During the severe impact onto the 20-degree slope (figure 8) the forward nose section recorded the following:

a.   longitudinal: 20 g's, 0.012-second duration, trapezoidal pulse, and
b.   vertical: 40 g's, 0.060-second duration, triangular pulse (20 g's fundamental pulse).

The mid-fuselage section floor experienced pulses such as 10 g's peak and 0.020 second duration.

FIGURE 8. CRASH TEST: IMPACT DAMAGE

Another FAA sponsored KRASH application to transport airplane accidents involved the CID full-scale crash test of a B-720 narrow-body transport (reference 4). Like the L-1649 test, the CID

represents a wing mounted 4-engine medium size transport category aircraft in the 159,000 to 195,000 lb. gross takeoff weight category.

In this crash scenario (figure 9), the impact conditions were as follows:

Airplane weight	=	192,383 lb.
Pitch attitude	=	0.0 degree
Roll attitude	=	13.0 degrees left wing down
Yaw attitude	=	13.0 degrees nose left
Longitudinal velocity	=	151.5 knots (245 ft/s)
Vertical descent rate	=	17.3 ft/s
Flight path	=	3.5 degrees

The airplane impacted first on the left wing (No. 1) outboard engine, then the left wing (No. 2) inboard engine, and subsequently impacted on the forward fuselage. The forward fuselage impact was estimated to occur 400 ms after initial engine impact. The forward fuselage impact conditions were estimated to be 14 ft/s sink speed, 0 to 2 degrees nose down pitch attitude, and a forward velocity of 150 knots.

Before the CID full-scale crash test, the FAA conducted a drop test of a similar airplane at the same impact conditions, except with no forward velocity, roll, or yaw. This test (the "Laurinburg" drop test) was to evaluate the airframe strength and failure characteristics for an aircraft similar to the CID test article under comparable attitude and sink speed impact conditions. A B707-131 airplane, which is 100 inches longer (20 inches forward of BS 620 and 80 inches aft of BS 960) than the CID test article, but of the same construction and design was used for this test. The test results, with the KRASH analysis of this impact, revealed the distribution of fuselage crush that could be anticipated for the CID. The KRASH model was refined in the fuselage underside crush and overall fuselage strength characteristics' areas. The CID and Laurinburg tests provided hard data concerning fuselage underside crush distances that might be experienced in a moderate impact. After the CID test, parametric analyses were performed, and an envelope of fuselage crush distribution was developed as shown in figure 10.

This discussion of transport category airplane accidents and full-scale crash tests revealed that these accidents and tests provide information data relevant to the auxiliary fuel tank installations. This relevance is demonstrated by the following:

a.   All the accidents/crash tests, except the Lockheed L-1011 Everglades accident, involved narrow-body airplanes.

b.   All the occupant injury hazards in accidents and tests were trauma related and the postcrash fire, or lack of such, did not influence passenger egress.

c.   All the cases, except the CID test, involved a fuselage sink speed between 17.3 and 37.5 ft/s.

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d.   The B-737, MD-81 and L-1649 cases involved forward velocities of between 110 and 164 ft/s during the more significant impact. These velocities compared favorably with the average 133 ft/s for ground-to-ground crash scenarios.

e.   The airframe fuselage characteristics for the B-727, a candidate test specimen, compared favorably with those of the B-737, MD-80, and CID aircraft. Table 1 shows this comparison.
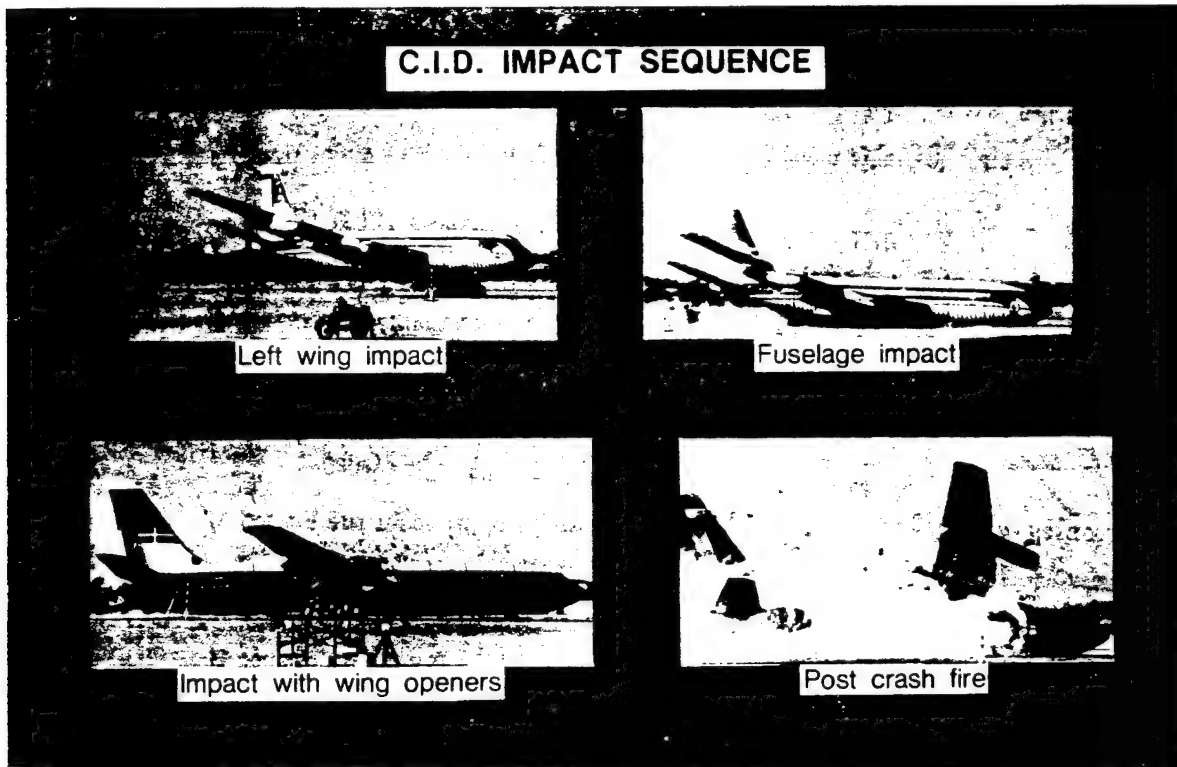

FIGURE 9. CID FULL-SCALE CRASH TEST SCENARIO
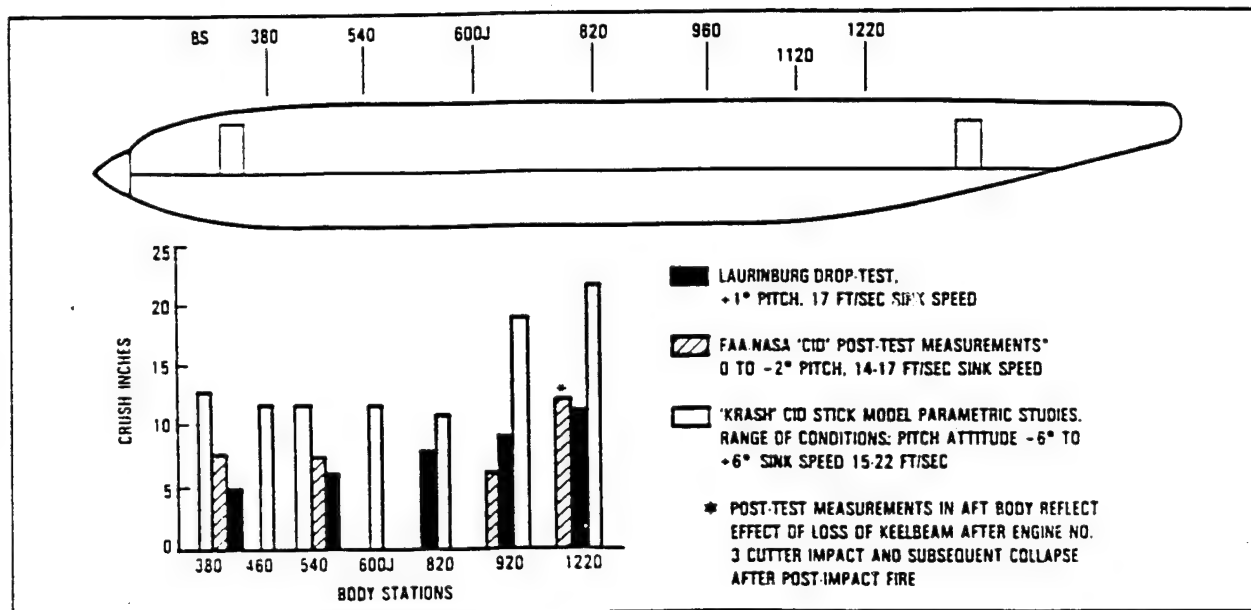
LOWER FUSELAGE UNDERSIDE CRUSH DISTRIBUTION

FIGURE 10. FUSELAGE CRUSH DISTRIBUTION

TABLE 1. COMPARISON OF TRANSPORT AIRCRAFT
STRUCTURAL CRASH CHARACTERISTICS

	B-727-200	B-737-400	MD-81	CID
Takeoff Weight (Lbs.)	173000	143000	147000	195000
Fuselage Diameter Fwd/Aft	13'2"/14'	13'2"	11'8"	14'2"
Passenger Floor Depth Fwd/Aft	4'5"/5'3"	5'	4'2"	5'8"
Fuselage Length	136'2"	105'7"	147'10"	145'
Cabin Width	11'8"	11'4"	10'1"	11'4"
Engine Configuration	3F	2F	3F	4W

2.4   CONFORMABLE TANK TEST CONFIGURATION.

Discussions were held with industry relative to obtaining fuselage mounted auxiliary fuel tanks. An industry source indicated that two sizes of conformable auxiliary fuel tanks are used in their B-727 and B-737 airplanes. The two sizes and their locations are (1) an 860-gallon tank installed in B-727 aft section, and (2) an 810-gallon tank installed in B-737 aft section or B-727 forward and aft sections. A typical fuel tank installation arrangement is shown in figure 11.
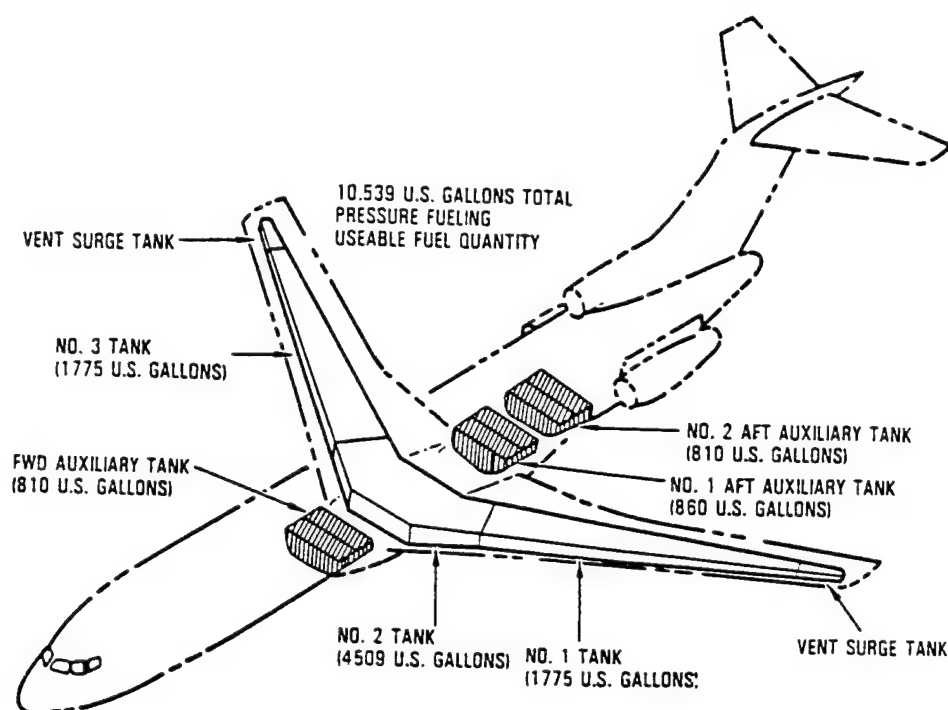

FIGURE 11. TYPICAL NARROW-BODY AIRPLANE CONFORMABLE AUXILIARY FUEL TANK INSTALLATION

The particular tanks that fit the above-mentioned installations are attached to the fuselage and floor as shown in figures 12 and 13. After consideration of available tank and fuselage configurations, it was decided to use a 500-gallon conformable tank in a B-737 fuselage section.
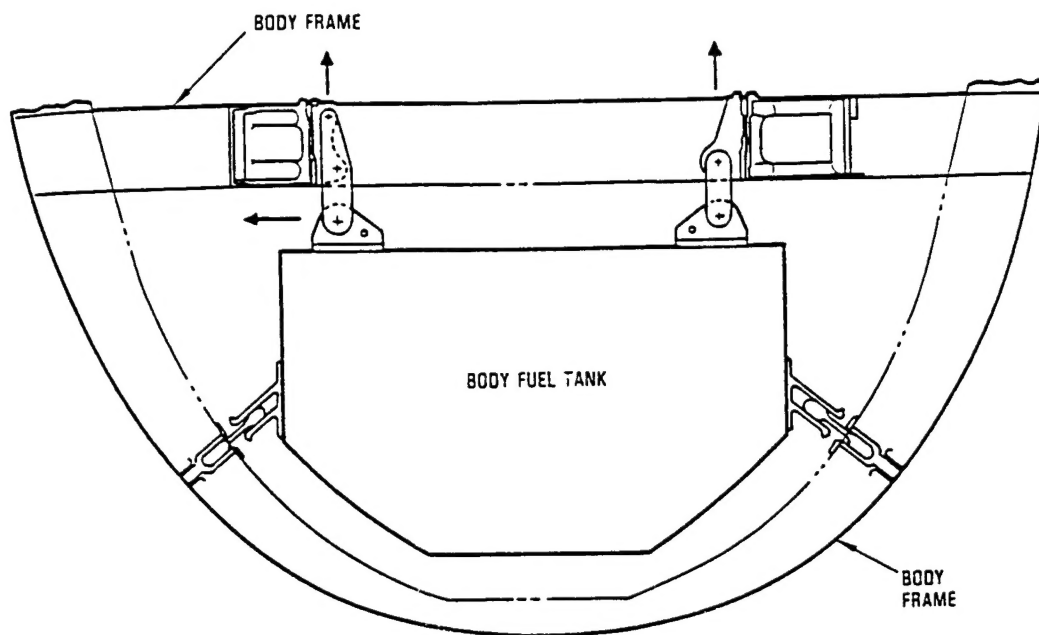
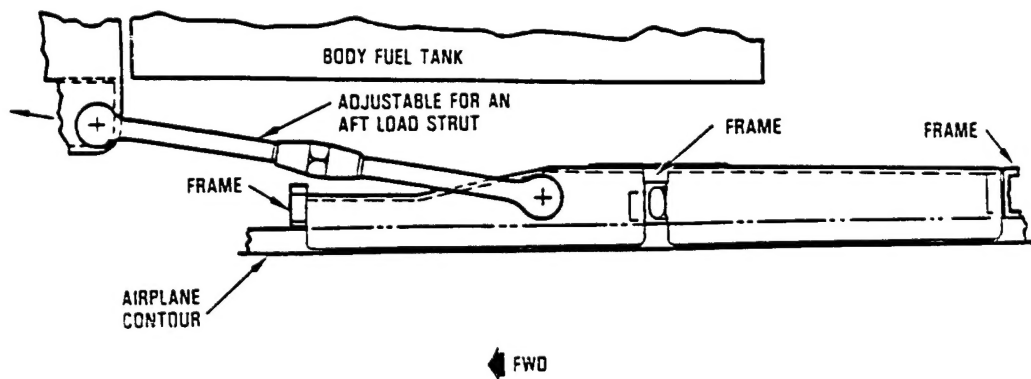FIGURE 12. CONFORMABLE AUXILIARY FUEL TANK INSTALLATION
ATTACHMENT LAYOUT

FIGURE 13. CONFORMABLE AUXILIARY FUEL TANK FORE-AFT ATTACHMENTS

2.5 PROPOSED CANDIDATE PROCEDURE TO EVALUATE FUSELAGE AUXILIARY FUEL TANK INSTALLATION PERFORMANCE UNDER CRASH LOADS.

As mentioned, these discussions indicate that fuselage installed auxiliary fuel tanks during severe, but survivable crashes can be exposed to substantial dynamic loads, and that there is the potential that their structural integrity can be compromised. The performance of the fuel tank installation is dependent on the design configuration, the location of the installation, and the composition and

direction of the dynamic forces. To test each auxiliary fuel tank design and installation is an impossible task, considering the time and cost of each test condition involved. The guidelines for crashworthy tank installations provided in the AC 25-8 may not address the appropriate loading conditions. To evaluate the range of auxiliary fuel tank installations under crash loading conditions, it is necessary to develop a procedure based on fundamental relationships relating to both crash scenarios and design concepts.

The following is the outline of a candidate procedure that can be used to evaluate fuselage auxiliary fuel tank installation performance in a dynamic environment. The procedure is to be based on using existing and anticipated test data, fuel tank installation design data, and simplified analytical procedures. The objective is to provide the simplest approach, by making available design and dynamic response relationships as charts, illustrations, and nomographs, where practical. The procedure is to be developed so that consideration will be given to dynamic pulse shape, magnitude and duration forcing functions, fuel tank configurations, fuel tank installation design loads, fuselage airframe structural integrity, and fuselage airframe configurations.

The following is a list of the type of information that is available:

      a.   Full-scale airplane test/accident data.
      b.   Airframe/section test data.
      c.   Calibrated KRASH modeling sensitivity.
      d.   Analytical methodology.
      e.   Fuel tank design and installation.
      f.   Fuel system components; size, location, and routing.

This information must be integrated into a practical procedure. The type of information that is, or will be, available suggests that a procedure for evaluating fuselage mounted auxiliary fuel tank installations should be semi-empirical. The procedure will evolve from the following outlined approach.

      a.   Analyze the results from the double-wall cylindrical auxiliary fuel tank vertical impact test.

      b.   Compare test results with prior analytical predictions.

      c.   Calibrate the analytical model based on the results of the test.

      d.   Calibrate the analytical model for the longitudinal pulse test data.

      e.   Extend the modeling applications to other auxiliary fuel tank installations (planned conformable) longitudinal and vertical impact tests and crash impact representations.

      f.   Develop semi-empirical relationships between auxiliary fuel tank installation characteristics and impact conditions and responses.

g.   Develop measures of performance and relate these measures to definable parameters, i.e., support load-impact velocity, tank acceleration to static load factor, clearance required to vertical impact velocity.

h.   Incorporate additional test data (as it becomes available) and refine the procedures, if necessary.

i.   Perform additional modeling analysis of other design concepts with different loading conditions.

j.   Relate the results to full-scale accident behavior.

k.   Provide a procedure consisting of applicable curves, tables, and models that can be used for different auxiliary fuel tank installation configurations.

3.   CONCLUSIONS.

1.   A fuselage airframe and auxiliary fuel tank installation has been suggested for the next phase of testing.

2.   Recent accident data have demonstrated that the current auxiliary fuselage tank test/analysis program is relevant to narrow-body airplanes with impact velocities found in severe, but survivable, accidents.

3.   Testing alone, without supporting analytical or semi-empirical procedures is too limited, time consuming, and too costly an approach to evaluate auxiliary fuel tank installation performance under crash conditions.

4.   A candidate procedure to evaluate fuselage auxiliary fuel tank installation performance under crash loads has been proposed.

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